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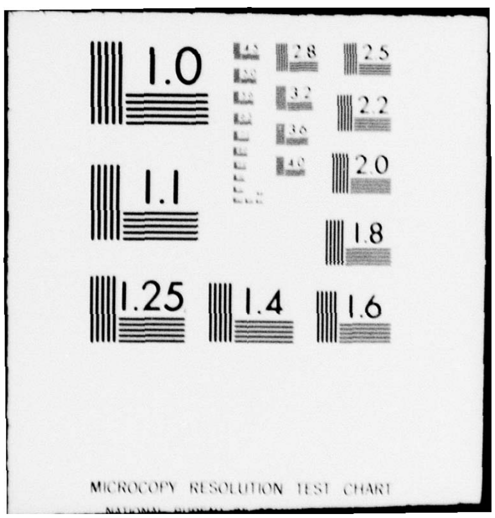
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ANNUAL INTERIM REPORT

# CHEMICAL INITIATION OF FAE CLOUDS

Submitted to:

Department of the Air Force
Office of Scientific Research
Directorate of Aerospace Sciences
Bolling AFB, Washington, D.C. 20332

Attention: Dr. Bernard T. Wolfson

Under Contract No. F049620-77-C-0097



Submitted by:

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E. T. McHale

ATLANTIC RESEARCH CORPORATION
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ARC No. 47-5711

October 1978

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| SINGLE-EVENT FAE | |

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

It is believed that the second-event system in FAE devices can be eliminated by development of a process in which very rapid fuel dispersion and simultaneous combustion are initiated by a single event. According to this concept, a central explosive charge would drive a highly reactive chemical agent such as chlorine trifluoride (CTF) into a surround of hydrocarbon fuel, with the effect that the fuel would be explosively dispersed and burned in the ambient air, and a FAE blast generated. Laboratory research is described in which small slugs of CTF and BTF (bromine trifluoride) were driven pneumatically into Diesel oil. (over)

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Laboratory research is described in which small slugs of CTF and BTF (bromine trifluoride) were driven pneumatically into Diesel oil (less than one gram quantities). The ensuing event was diagnosed by high speed motion pictures and blast gages. An FAE effect was reproducibly observed with BTF. With CTF it was found that the agent-fuel reaction is so rapid that a counterforce develops at the interface of the liquids and prevents thorough mixing and reaction. In larger-scale field tests that are planned, CTF will be explosively driven into Diesel oil, thus eliminating this hindrance.

It is considered that proof of concept has been demonstrated in the sense that a blast wave has been produced by chemical initiation of a fuel-air mixture. However, this has been accomplished on laboratory scale only. The concept depends on rapid fuel dispersal accompanied by combustion. These aspects of the concept are scale-dependent. Therefore, larger-scale experiments are required before it can be certain that the concept will be applicable to operational FAE systems.

## 1.0 INTRODUCTION

This report covers experimental and theoretical studies that have been performed under the subject contract between May 1, 1977 and September 30, 1978. The objective was the development of a concept of self-detonating FAE clouds that would eliminate the need for and the penalties associated with a second-event system. The approach that has been taken comprises small-scale laboratory experiments to establish the principle of blast generation by extremely rapid fuel dispersion and combustion, and the design of field tests on a sufficiently large scale for demonstration of the concept.

There are two possibilities for eliminating second-event systems: Either the FAE cloud is generated without ignition, as in the present state of the art, and then by simultaneous dispersion of a chemical agent, or by the chemical constitution of the fuel, the cloud is made to detonate spontaneously after an induction period; or fuel dispersion and combustion occur simultaneously at such high rate that an effective blast-generating piston force is maintained throughout the process of cloud generation and combustion. The first possibility has received only cursory attention in the present studies, because its implementation as a single-event FAE system appears to be rather difficult. The second possibility seems to be feasible and much less complicated. The basic principle is already known from the blast augmentation that occurs with underoxidized explosives in air by combination of the fuel residue of the detonating charge; that is, the combustible detonation products mix and burn with air at such high rates that the combustion energy makes an effective contribution to the blast wave. A FAE cloud would produce a blast wave analogously if the fuel were made to disperse and burn at such high rate that the cloud/air interface moves at a velocity comparable to the particle velocity in a fuel/air detonation wave. This leads to the concept of a FAE system in which the primary explosive charge drives a fluorine agent such as CTF ($ClF_3$) or BTF ($BrF_3$) into a surround of hydrocarbon fuel such as Diesel oil, which accordingly would disperse and burn like a detonating high-explosive. In a cylindrical configuration the core of the system would be a rod of a solid high-explosive surrounded by a stainless-steel jacket in which the fluorine agent is safely and durably incased. There is sufficient experience on the containment of such agents by stainless steel to make it certain that such system can be designed to meet the requirements of munitions safety. Detonation of the high-explosive would shatter the jacket and inject the agent into the surrounding hydrocarbon fuel. The resulting rapid dispersal of the fuel in the ambient atmosphere would sustain a blast wave depending on the mass flow generated by the process of dispersal and combustion.

Exploratory open-air tests have been performed in the laboratory by pneumatically driving small slugs of liquid BTF and CTF into Diesel oil. For practical reasons the fuel quantity was limited to volumes of less than one milliliter, which is the order of $10^{-6}$ to $10^{-7}$ times smaller than the fuel quantity in full-scale FAE systems. At this small scale, the blast generation by fuel dispersal and combustion requires ejection of atomized fuel particles into the ambient-air to radial distances of the order of 10 cm within less than about 300 microseconds. The ejection momentum that was achievable in these experiments fell short of this requirement but nevertheless did yield a significant augmentation of the blast by fuel/air combustion. When the ambient atmosphere was oxygen instead of air and the required ejection distance was accordingly reduced to the order of 5 cm, the blast effect was increased to the limit of safe laboratory experimentation. These data lead to the expectation that a FAE effect utilizing most or all of the combustion energy of the fuel can be demonstrated by increasing the test scale and using an explosive charge for driving the agent into the fuel. Accordingly, field tests are planned in which the fuel quantity is of the order of a thousand times larger than in the laboratory experiments, and the agent is contained in a small annulus of stainless steel surrounding a small explosive charge.

## 2.0 LABORATORY EXPERIMENTS WITH BTF, CTF AND DIESEL OIL

### 2.1 Apparatus and Experimental Procedure

The apparatus and details of the test configuration are shown in Figures 1 and 2. An 0.2 cc slug of liquid BTF in a 0.25 cm diameter U-tube of Pyrex glass is driven by compressed air at 80 psig into 0.6 cc of Diesel oil contained in a cylindrical brass cup of 1.0 cm diameter and 1.7 cm height. A 1/16-inch hole in the bottom of the cup connects the volume of Diesel oil with the diaphragm of a Kistler pressure gage. The gage is shielded from contact with the fuel oil by a buffer of Kel-F oil and additionally protected by a thin Teflon film. A 5/8-inch diameter Atlantic Research blast gage with a 3/4-inch long sensor is mounted above the cup, with the stream-lined front end of the cylindrical steel body aligned with the cup as shown, and the sensor protected by a thin Teflon film. The distance between the cup rim and the center of the sensor is 7.5 inches. The FAE cloud emerging from the cup was photographed with a Beckman and Whitely high-speed framing camera which accommodates two rows of 110 images each on its approximately 34-inch drum periphery, with successive exposures alternating from one row to the other. Illumination was provided by an Ascorlight photoflash. At a drum speed corresponding to 0.2 milliseconds interval between exposures in one row, or 0.1 milliseconds between the alternating exposures in both rows, the flash illumination and the flame luminosity decayed sufficiently within one drum revolution to avoid double exposures. The photoflash and the 2-channel oscilloscope for recording the signals of the blast gage and the Kistler gage were triggered simultaneously by a mercury switch actuated by the pressure release, as shown in Figure 1. The switch gap was adjustable for proper timing.

### 2.2 Experiments with BTF

The discharge of BTF from the tube end above the cup is visible in the motion pictures. The sketches in Figure 3 are drawn from photographs taken with the drum camera at close range, with the cup removed and a sand-box placed under the tube. It is seen that the liquid emerges from the tube as a slug traveling at 1.8 cm/millisecond velocity. The tip of the slug reaches the spot at which it would touch the level of the Diesel oil after

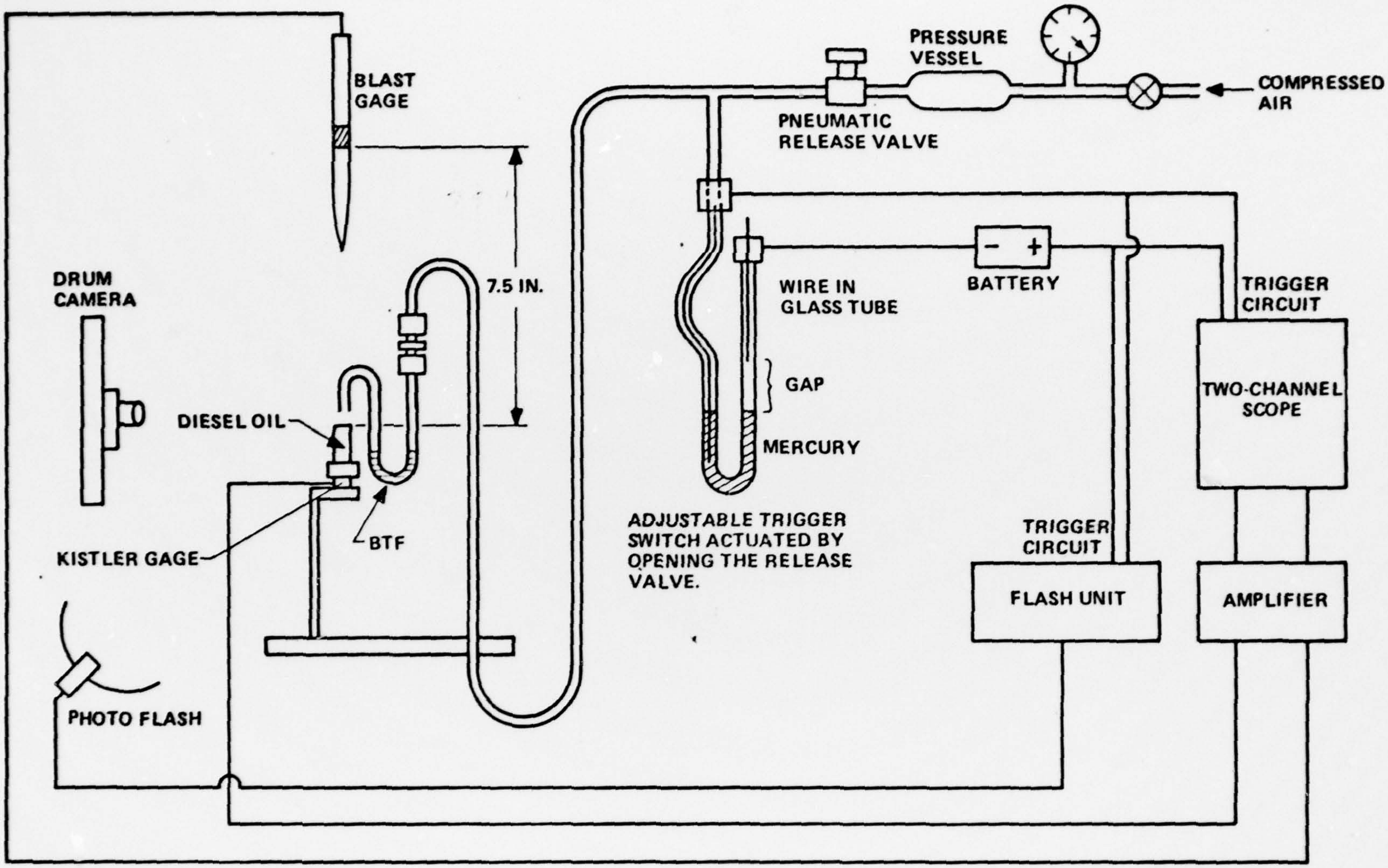



Figure 1. Scheme of Apparatus.

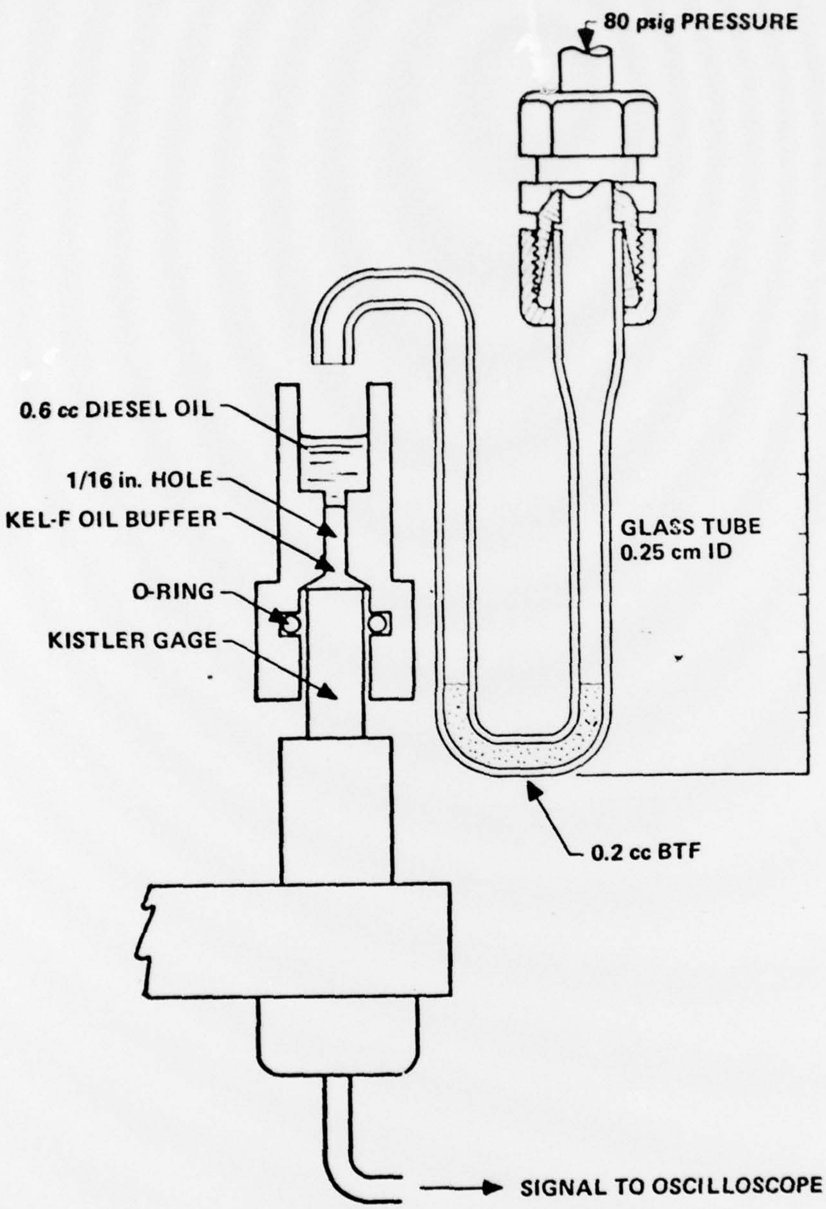



Figure 2. Test Configuration. For Tests in a Nitrogen Atmosphere the Assembly was Placed in a 1½' X 2' Glass-Wool Padded, Open-Top Cubicle with Observation Window.

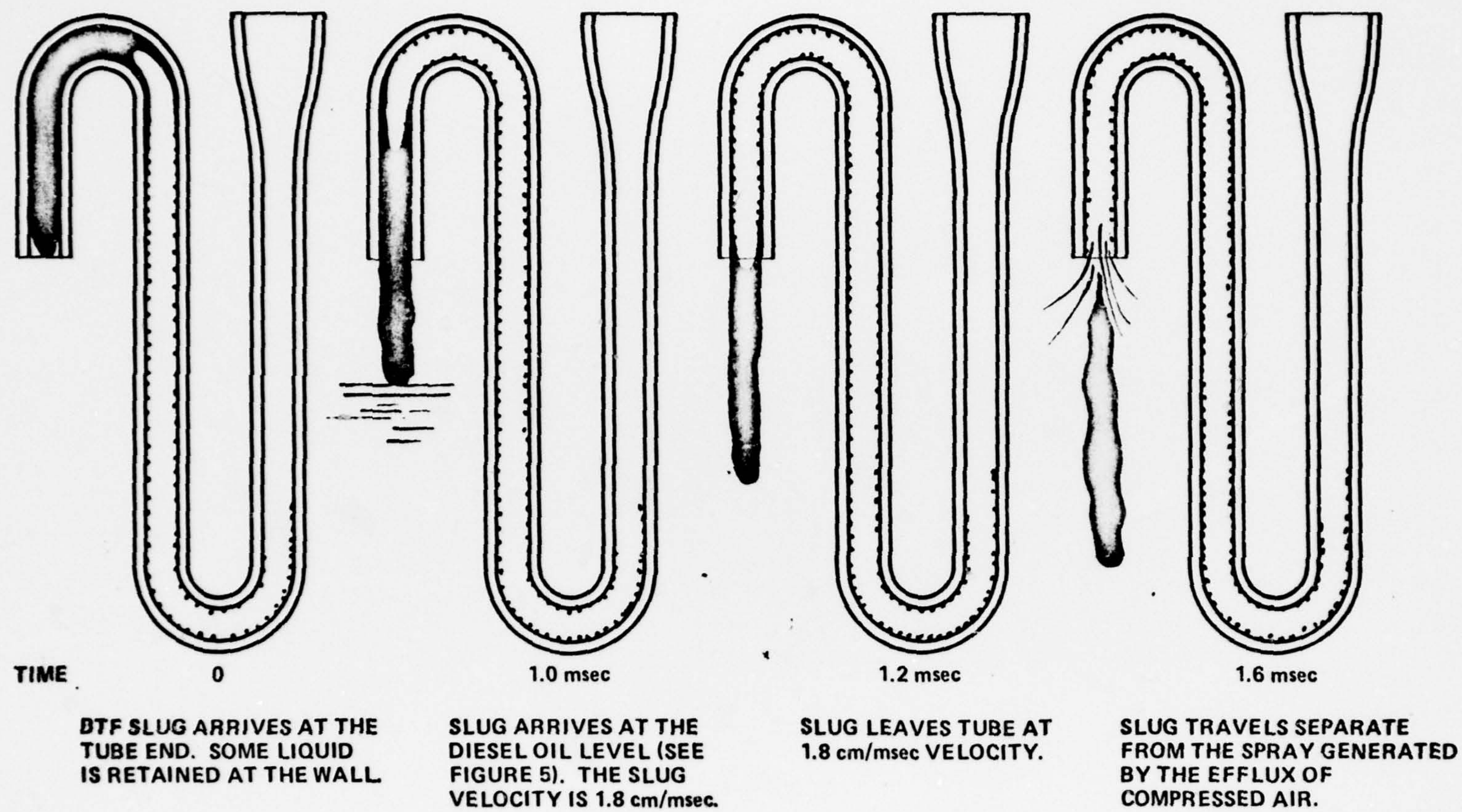



Figure 3. Discharge of BTF From the Glass Tube at 80 psig Pressure.

precisely 1.0 millisecond, and after approximately 1.5 to 1.6 milliseconds the slug becomes detached from the spray that is generated by the efflux of compressed air and entrainment of the liquid retained at the tube wall. The volume of the slug is calculated to be 0.09 cc on the assumption that its diameter corresponds to the tube diameter of 0.25 cm. The actual value should be smaller in view of the boundary layer at the tube wall. The slug would be completely below the original level of the Diesel oil in about 1 millisecond after the initial contact with the oil. However, as shown below, the Kistler gage records an explosive pressure rise starting at about 0.8 millisecond after contact, so that the total volume of BTF involved in the process is significantly less than 0.09 cc and may be less than 0.07 cc. This places the volume ratio of BTF to Diesel oil in the range of 0.1. The densities of BTF and Diesel oil are 2.5 and 0.85 g/cm$^3$, respectively, so that a volume ratio of 0.1 corresponds to a weight ratio of 0.3.

Figure 4 shows a composite record of a typical explosive event starting from the instant of impingement of the BTF slug on the Diesel oil. The volume of BTF that has passed at any time below the original level of the oil is calculated on the basis of 1.8 cm/millisecond slug velocity and an 0.25 cm cylindrical slug diameter. The reaction between BTF and oil presumably occurs along a turbulently increasing interface and generates high-temperature gas, which at atmospheric pressure would exceed the liquid volume by a factor of the order of $10^4$. The effect is seen to be a sequence of periods of pressure increase followed by pressure relief due to ejection of fluid material from the cup. There is an initial phase of 0.5 millisecond duration during which approximately 0.04 to 0.05 cc BTF enters the cup and the pressure increases to about 1000 psi. Subsequently, the pressure decreases and fluid is observed to be ejected in the form of a cloud. After about 0.8 milliseconds and an additional flow of about 0.02 cc BTF, there is a short period of very rapid pressure increase followed by very rapid pressure decrease and fluid ejection. During the latter phase the blast gage above the cup registers a substantial pressure wave, allowing for 0.6 millisecond of travel of the wave at 33 cm/millisecond over the distance of 7.5 in. (19 cm). A cloud is formed which expands more or less spherically at a radial velocity which is found to be initially about 4 cm per 0.1 millisecond, or 400 cm/sec. The Kistler gage registers subsequent pulses of

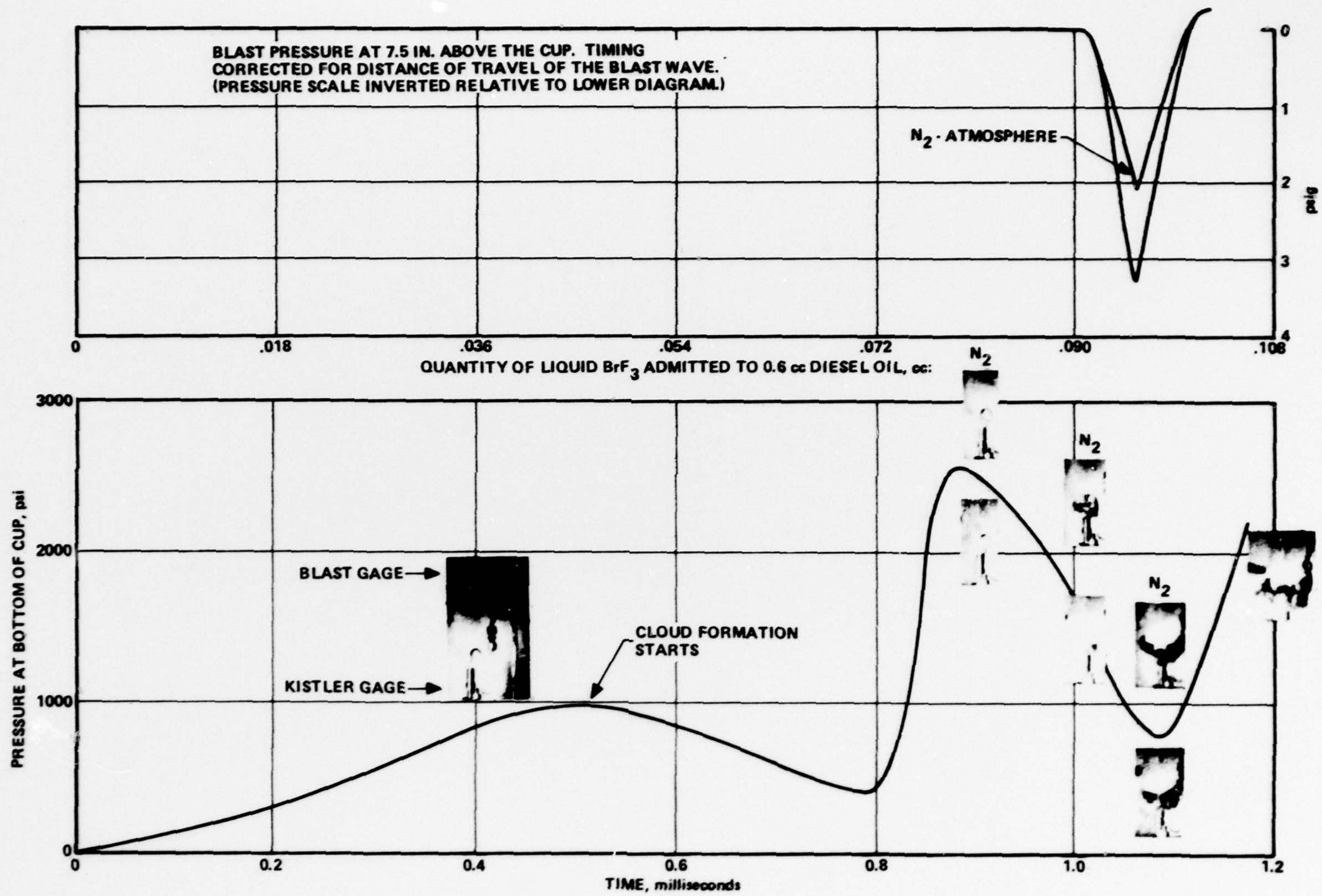



Figure 4. Unconfined Microscale FAE Clouds in Air or Nitrogen.

pressure increase and decrease which show that some oil remains in the cup and reacts with the incoming BTF and perhaps with BTF remaining in the cup, but these pulses produce only weak signals at the blast gage.

The participation of the fuel-oxygen reaction in the cloud expansion is demonstrated by performing these experiments in atmospheres of air and nitrogen. As shown in Figure 4, the blast pressure in air is considerably larger than in nitrogen. However, the cloud attenuates before sufficient air for combustion of the dispersed oil has passed into the cloud, and there is a period of afterburning with only weak pressure signals.

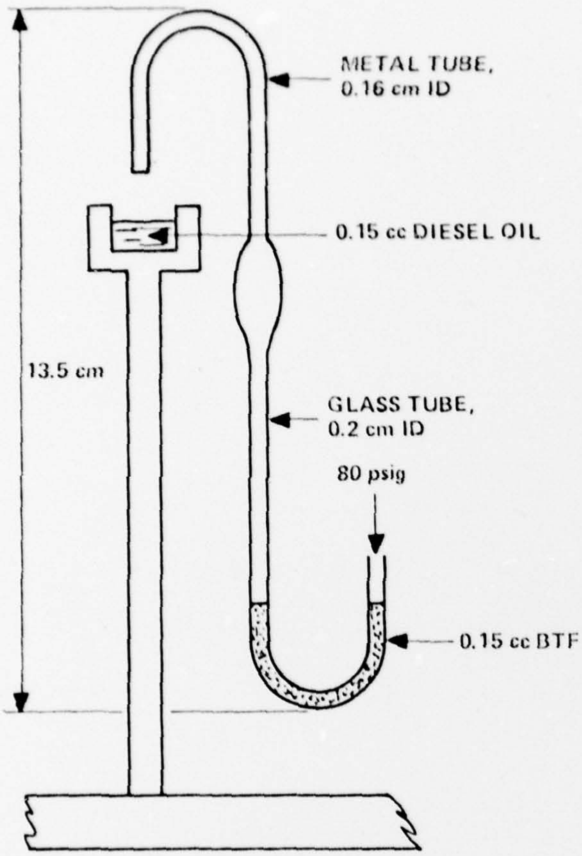
The effect of the fuel-oxygen reaction is further recorded in other experiments in which the quantity of oil in the cup and the rate of BTF injection were considerably smaller and the surrounding atmosphere was nitrogen, air, and oxygen, respectively. The data and the test configuration are shown in Figure 5. In this case, the blast pressure in air was also larger than in nitrogen, but the percentage increase was less than in the experiments in which the test scale had been increased. With oxygen, the blast gage registered a blast pressure of 5 psig at the distance of 19 cm from the cup. This was close to the tolerable limit in the laboratory environment, and the test was not repeated in the later experiments.

## 2.3 Experiments with CTF

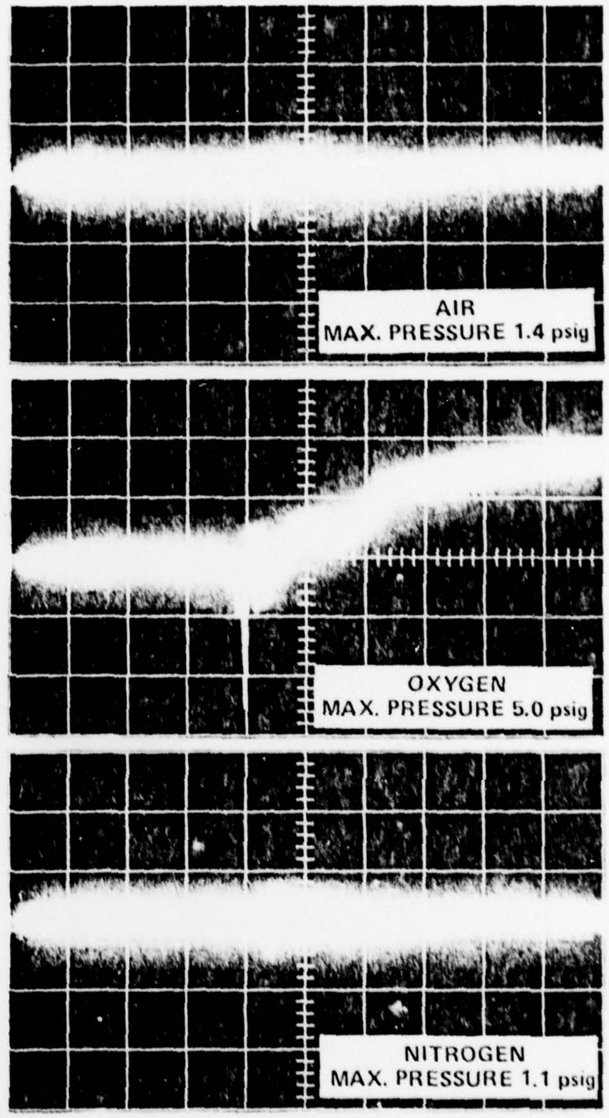
An 0.22 cc slug of liquid CTF was introduced into the 0.25 cm diameter glass U-tube by connecting the tube to a CTF-vapor line and condensing the vapor with dry ice. In other respects the experimental procedure was identical with the procedure used in the experiments with BTF.

The experimental record was entirely different from the record shown in Figure 4. The Kistler gage recorded a sharp pressure rise beyond the limit of the instrument within a time of no more than 0.1 millisecond. There was a bright flash of flame, but the blast effect was audibly less than with BTF and the blast gage registered only a series of weak pressure pulses.

It is apparent that the reaction between CTF and Diesel oil is so rapid that the initial contact of the liquids generates a very large force which is pressing the oil into the cup and deflecting the jet of CTF, so that no significant quantity of CTF can enter the cup. It seems that the oil was ejected from the cup due to relaxation of its elastic compression




EARLIER TEST CONFIGURATION. FOR TESTS IN OXYGEN AND NITROGEN ATMOSPHERES THE ASSEMBLY WAS PLACED IN AN OPEN TRANSPARENT CYLINDER OF 8 IN. DIAMETER AND 13 IN. HEIGHT.




TIME, 2 msec/cm

BLAST PRESSURE AT 7.5 IN. ABOVE THE CUP

Figure 5. Experiments in Atmospheres of Oxygen, Air, and Nitrogen.

rather than by explosive reaction with the fluorine agent inside the cup, as occurs with BTF. Thus, the dispersal process was relatively slow and no significant FAE effect developed, although a vigorous flame reaction occurred due to the dispersal of CTF above the cup.

It seems that a FAE effect much exceeding the effect in the BTF experiments could be obtained if the slug of CTF were driven with a much greater force than the force available from the pneumatic system that was used in these experiments. However, this cannot be readily managed in the laboratory and has not been attempted.

## 2.4 Discussion

In the experiments with BTF (Figure 4), an ejection of fluid from the cup and corresponding pressure relaxation occurs at 0.5 milliseconds after admission of BTF, at which time the oil in the cup is pressurized to about 1000 psi. It seems that up to this time the BTF has not penetrated far into the oil and that the ejecta consist mostly of products of the BTF/oil reaction. The subsequent sharp pressure rise suggests that at this stage the free-radical concentration and the interface between BTF and oil increase rapidly, the latter presumably due to Taylor instability. At about 2500 psia a large pressure relaxation occurs due to ejection, which this time comprises a major portion of the contents of the cup. The pressure drops within 0.2 milliseconds to about 800 psi, so that the average pressure is 1650 psi, and the cross-section of the cup is 1 $cm^2$, which yields an average force of $1.1 \times 10^8$ dyne acting on the mass of oil being ejected. The cup contains 0.6 cc = 0.5 g of oil, which if totally ejected would within 0.2 milliseconds be accelerated to the velocity $V = (1.1 \times 10^8 \times .2 \times 10^{-3}/0.5)10^{-2} = 440$ meter/second. Experimentally it is found that the cloud boundary moves at an initial velocity of about 400 m/sec. This represents the mass velocity of the ejected and finely atomized oil plus BTF products plus entrained air, which at a cloud radius of about 4 cm has a mass somewhere between 0.1 and 0.3 g depending on the cloud temperature and pressure. The data are consistent with the view that most, but not all, of the oil is ejected from the cup at this stage, and this is confirmed by the subsequent pressure pulses recorded by the Kistler gage.

At a mass velocity of 400 m/sec the shock Mach number is about 2 and the shock pressure is about 4 atmospheres, but the shock wave attenuates sharply due to divergence of the wave propagation and decrease of the momentum of the cloud gases, so that the blast gage at 19 cm distance from the cup receives only a small signal. In air, the signal is about double the strength of the signal in nitrogen, which shows that the cloud momentum is increased by combustion and a FAE effect is obtained. The effect is small, which shows that in these experiments the rate of fuel disperson is rather low. However, even at this low dispersion rate the FAE effect becomes large when the ambient air is replaced by oxygen. As has been mentioned, an experiment with oxygen was performed on a considerably smaller scale and not repeated on the scale shown in Figure 4.

In order to obtain a similarly large FAE effect in air the cloud should entrain all the air within about 10 cm radius while expanding at sonic velocity or more, in which case the process of fuel dispersion and combustion would have to be completed in less than about 300 microseconds. This was not achieved in the present tests, but neither has the potential of BTF been utilized efficiently. Due to the small mass of oil in the cup the ejection occurred already at a pressure of 2500 psi = 0.175 kilobar, whereas under confined conditions the BTF/oil reaction would certainly generate pressures of 10 to 100 kilobars with correspondingly much higher acceleration of the surrounding oil. This would be further improved by using the more energetic CTF as illustrated by the heats of reaction (calculated from Bureau of Standards data)

$$ClF_3 + 2(-CH_2^-) = 2C_s + 3HF + HCl + 168.5 \text{ kcal/mole CTF}$$

and

$$BrF_3 + 2(-CH_2^-) = 2C_s + 3HF + HBr + 90.7 \text{ kcal/mole BTF.}$$

In the present experiments CTF could not be driven into the oil because it reacts too rapidly. However, effective confinement can be obtained in tests on a larger scale, and it should be possible to drive CTF into the oil by using the detonation pressure of a high-explosive, which may be augmented by a shaped-charge configuration.

## 3.0 PRELIMINARY ANALYSIS OF LARGER-SCALE RESEARCH

### 3.1 Proposed Test Configuration

A general design of an experimental FAE device for tests involving several hundred grams of hydrocarbon fuel is shown in Figure 6. An annular stainless-steel vessel containing liquid CTF is surrounded at its periphery by Diesel oil and contains a solid high-explosive charge in its core. Confinement for the period between detonation of the charge and ejection of the fluids is provided by sandwiching the assembly between massive steel blocks. The central block of explosive is detonated simultaneously from both faces by two equal lengths of primacord which are initiated simultaneously by a single detonator. The two colliding detonation waves generate a strong lateral shock comparable to a shaped-charge effect, which shatters the CTF-container and drives the fluid into the oil surround. The CTF/oil reaction plus the primary detonation drives the fuel into the surrounding atmosphere, forming a cloud of atomized oil and generating a strong primary air shock. The oxygen carried into the cloud by air entrainment reacts instantly with the fuel and increases the cloud momentum, thus generating the FAE effect.

Initial tests are expected to be performed with 350 cc (300 gram) of Diesel oil and 35 cc (63 g) of CTF. The overall diameter of the device is about 7 inches and the space between the steel blocks is about 5/8 inch wide. The CTF annulus has an outer diameter of 2 inches and an inner diameter of 1/2 inch with corrections for the wall thickness. The volume of the explosive charge is approximately 5 cc which corresponds to a weight of about 8 grams.

### 3.2 Estimated Test Performance and Program Development

The FAE effect to be achieved in the proposed tests depends on the drive imparted to the fuel oil by the detonation of the explosive core and the detonative reaction between the oil and the injected CTF. A reliable prediction is not possible, but a rough estimate may be made.

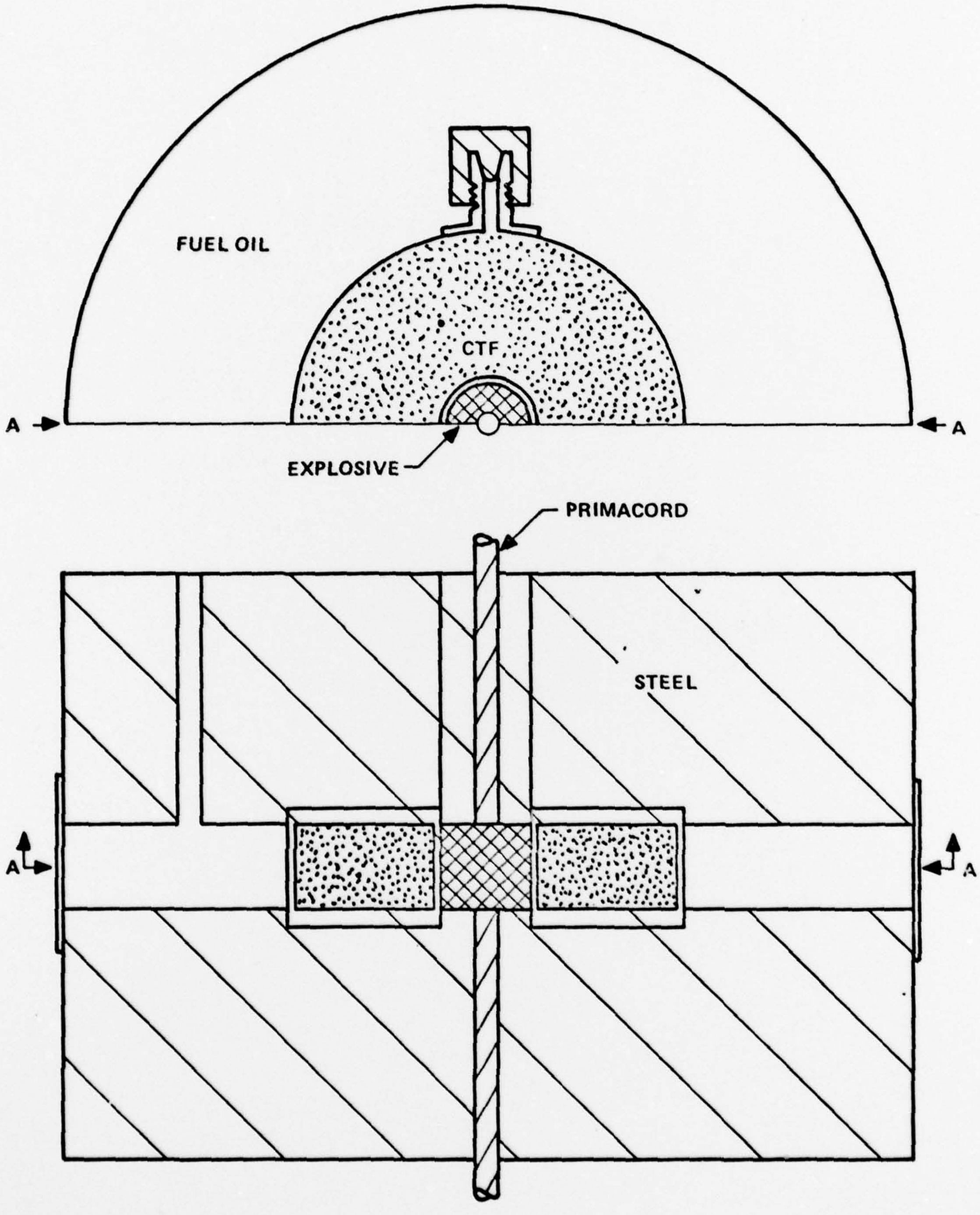



Figure 6. Concept of Test Configuration (No Scale).

If the pv -work generated by the explosive is taken to be of the order 1 kcal per gram and that of the CTF/oil reaction to be no less than one-half of the heat release of 168.5 kcal per mole (1.82 kcal/g CTF), one obtains from 8 gram explosive and 63 gram CTF a total pv-work of no less than 65 kcal = $6.5 \times 10^6$ foot-poundals for driving 300 g oil (minus 19 g consumed in the reaction), or 0.62 pounds. The oil would thus be injected into the ambient atmosphere at a velocity of not less than $\sqrt{2 \times 6.5 \times 10^6/.62}$ = 4,600 ft/sec = 1400 m/sec, and would produce a shock wave in the air which may be of the order of 1700 m/sec, or about Mach 5. The subsequent fuel dispersion and combustion would, to a considerable distance from the explosion center, proceed via Taylor instability, and as this effect subsides it would be continued by turbulence which is supported by the randomly distributed combustion centers in the cloud. A schematic concept of the process is illustrated in Figure 7. Temperatures and free-radical concentrations within the cloud are expected to remain at sufficiently high levels throughout the process to allow combustion to proceed at the rate at which oxygen enters the cloud, until the fuel supply approaches exhaustion. The total required combustion air occupies a volume of about 7 feet spherical radius. It is therefore required that the cloud momentum should be sustained at sonic velocity or higher up to this distance, and that the process of fuel dispersion and combustion should therefore be substantially completed within less than about 6 milliseconds. Considering the fact that a weak FAE effect was already obtained in the very inefficient laboratory tests, it seems plausible that a substantial FAE effect will be obtained in the proposed tests.

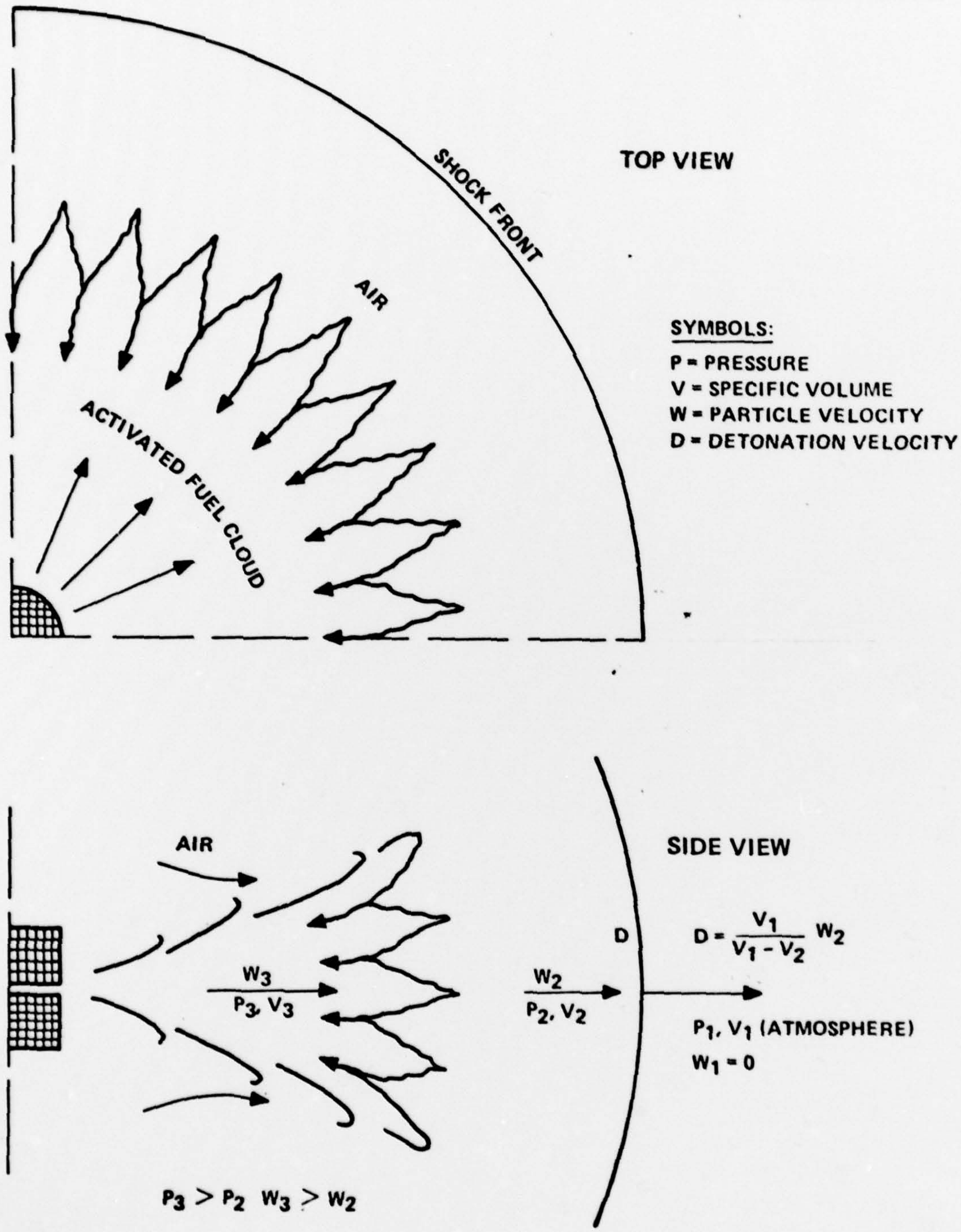



Figure 7. Scheme of Air Entrainment and Shock Generation.